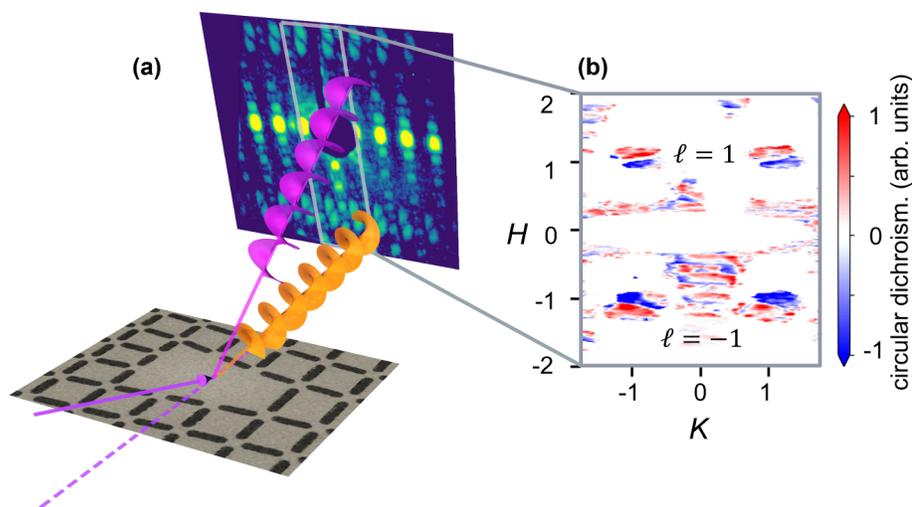


# Spiraling Beams Differentiate Antiferromagnetic States



(a) In this experiment, circularly polarized x-rays were scattered by an antiferromagnet array with a lattice defect, producing spiral beams with orbital angular momentum (OAM) of both positive and negative helicity. (b) The resulting diffraction patterns differ depending on the polarization and helicity of the beam (an effect known as dichroism). The peaks with a diffraction order ( $H$ ) of +1 and -1 have positive and negative helicity ( $\ell$ ), respectively. Each peak has half positive (red) and half negative (blue) circular dichroism, with the pattern inverted for opposite helicities.

## X-ray beams with a twist

X-ray experiments are an important tool for understanding the electronic and magnetic properties of materials. The polarization (i.e., the direction of the oscillating electromagnetic field) of x-rays is often used to probe anisotropy or chirality. A property of x-rays that has yet to be utilized in experiments is their orbital angular momentum (OAM). X-rays with OAM have an azimuthally varying phase, which means the phase twists as the x-rays propagate. This leads to a gradient in the electromagnetic field, which could cause the twisted photons to have different interactions with materials.

X-rays with OAM have a helicity  $\ell = \pm 1$ , which corresponds to whether the phase is twisting in the clockwise or counter-clockwise direction. Similar to how polarization is used in experiments, OAM can be used to probe chirality and magnetism, and potentially more exotic properties like topology. It could also improve the resolution of x-ray imaging and microscopy techniques. In this work, researchers showed how helicity-dependent effects in resonant x-ray scattering (RXS) can be used to investigate the magnetic configuration of a lattice.

## Scientific Achievement

Using spiraling x-ray beams generated at the Advanced Light Source (ALS), researchers differentiated between energetically equivalent (“degenerate”) states in an antiferromagnetic lattice.

## Significance and Impact

The work shows the potential of these beams to probe properties that would otherwise be inaccessible, to better understand phenomena of fundamental interest and for applications such as spintronics.

## Creating twisted light

One way to create x-ray beams with OAM is by scattering from a topological defect. Here, a square lattice of permalloy nanomagnets was synthesized on a silicon substrate. Two extra nanomagnets were inserted into the center to create a topological edge defect.

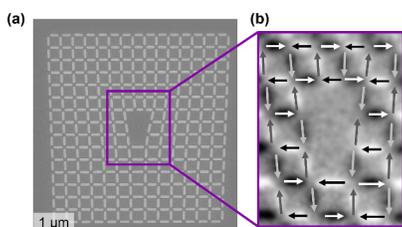
At ALS Beamline 11.0.1.1, photoemission electron microscopy (PEEM) with x-ray magnetic circular dichroism (XMCD) was used to image the magnetic configuration. The results showed that the nanomagnets order antiferromagnetically, where the direction of magnetization alternates on adjacent nanomagnets.

To investigate what OAM beams can reveal about the antiferromagnetic lattice, RXS experiments were performed with circularly polarized light at ALS Beamline 7.0.1.1 (COSMIC Scattering). Scattering from the nanomagnets created beams with both positive and negative OAM helicities, and circular dichroism was used to compare beams of opposite helicity at distinct antiferromagnetic peaks.

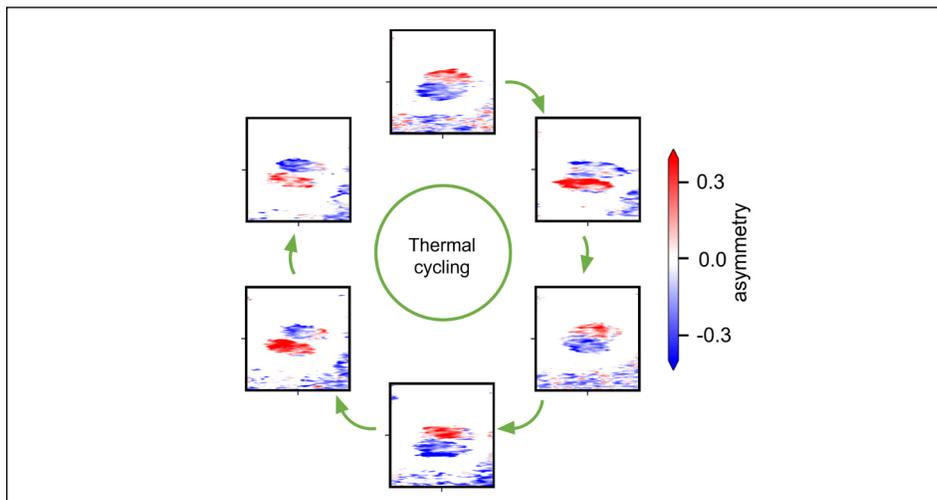
### Helicity-dependent scattering

The researchers found that the circular dichroism has a distinct pattern, which is inverted for beams of opposite helicity. Furthermore, the antiferromagnetic lattice forms in one of two degenerate ground states, and the helicity-dependent circular dichroism can be used to distinguish between them.

Since the two ground states are degenerate, they should form with equal probability if the antiferromagnet is heated and returned to room temperature. To test this, the nanomagnet array was repeatedly heated to 380 K and cooled. At room temperature, both configurations appeared with about equal probability, as expected for random thermal switching between two degenerate ground states.



(a) A scanning electron microscope image of the nanomagnet array with a topological defect. (b) The magnetic configuration, measured using PEEM XMCD, shows the antiferromagnetic ordering of the lattice.



Changing the antiferromagnetic ground state. When heated to 380 K and cooled back to room temperature, one of two antiferromagnetic ground states randomly forms. Here, the room-temperature dichroism is shown for each of six thermal cycles.

This is one of the first experiments to show how the helicity of light can be used to study magnetism. Information about the real-space magnetic configuration of a lattice is usually inaccessible in such experiments, so this work demonstrates the potential of OAM beams for gaining information beyond what is typically obtained in other experiments.

Promising future avenues include using OAM beams in resonant diffraction studies of traditional antiferromagnets, in nano-diffraction studies of domain walls and defects, and, if an OAM beam can be used to measure specific spin sublattices, for directly measuring spin currents.

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**Publications:** M.R. McCarter, A.I.U. Saleheen, A. Singh, R. Tumbleson, J.S. Woods, A.S. Tremsin, A. Scholl, L.E. De Long, J.T. Hastings, S.A. Morley, and S. Roy, "Antiferromagnetic real-space configuration probed by dichroism in scattered x-ray beams with orbital angular momentum," *Phys. Rev. B* **107**, L060407 (2023), doi:10.1103/PhysRevB.107.L060407.

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